

RELATIONSHIP OF MERCURY
LEVELS IN SPORTFISH
WITH LAKE SEDIMENT AND
WATER QUALITY VARIABLES

R.A.C. PROJECT NO. 353 C



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SUMMARY

Tissue mercury levels in smallmouth bass and walleye were weakly correlated with background sediment mercury levels. Mercury levels in lake trout were not correlated with background sediment mercury concentrations. Background sediment mercury levels were not selected in multiple regression analysis as a predictor of fish mercury concentration.

Results suggest that geological mercury levels do not account for differences in fish mercury levels observed between lakes. Mercury concentrations in standard size smallmouth bass (31 cm) and walleye (41 cm) were negatively correlated with water quality variables reflecting water hardness and acidity. Therefore, fish of these species in low pH lakes tend to have elevated mercury levels relative to circumneutral lakes.

Mercury concentrations in standard size (44 cm) lake trout were positively correlated with dissolved organic carbon and lake area. It is recommended that more studies examine the influence of humic substances on mercury accumulation in fish, with emphasis on lake trout. The lack of correlation between mercury levels in lake trout and water pH may be a function of biological factors (eg. diet) influencing trout mercury concentrations within individual lakes.

The mercury concentration of an average sized (41 cm) walleye (517 ng/g) exceeds the unlimited consumption guideline of 500 ng/g for mercury in fish set by Health and Welfare Canada.

There was a very high correlation between standardized mercury concentrations in smallmouth bass and walleye, and between smallmouth bass and lake trout. The development of interspecies correlations could provide a useful management tool. The results of this study support the premise that a number of lake physical and chemical variables simultaneously influence mercury accumulation and availability within lakes.

OBJECTIVES

The primary objectives of this study were:

- a) to examine the relationship between mercury levels in sportfish and natural sediment mercury content of lakes, and
- b) to use appropriate statistical methods to examine the relationship between mercury levels in fish with mercury levels in lake sediments and lake physical and water quality variables.

1. INTRODUCTION

It is well established that mercury levels in fish even from waters remote from direct pollution vary significantly between lakes, but the overall factors determining spatial variability remain obscure. A number of studies have reported that fish mercury levels are elevated in low pH lakes, suggesting that lake acidification is a factor affecting mercury uptake in fish (Brouzes et al 1977; Suns et al 1987; Wren and MacCrimmon 1983; Bjorklund et al 1984). A variety of other biotic and abiotic variables are also known to influence mercury uptake in fish (eg. Richman et al 1988; Verta 1984; 1985).

Mercury occurs naturally in combination with sulphide (HgS) known as cinnibar (Boyle 1974). The mercury content of ores generally increases with increasing zinc content, indicating that most mercury is present as a constituent of sphalerite (ZnS) (MacLatchy and Jonasson 1974).

Bedrock geology and soil type are known to have a profound influence on the chemical composition of many plant species, which in turn can directly affect the levels of certain elements (e.g. Se, Cu, Mo) in terrestrial animals. However, the relationship between bedrock geology and mercury burdens in fish has not been seriously investigated.

Lake sediment geochemistry can be used as a reflection of watershed geology (e.g. Coker and Nichol 1975), which in turn may influence mercury levels in aquatic biota. On the Precambrian Shield there are well defined areas where mercury levels in surface soils are high (Kettles, pers. commun.). Such areas are normally associated with mineralization and presence of sulphide ores (Allan et al. 1974). A recent examination of fish mercury levels in reservoirs across Canada identified that certain discrete areas were predisposed to elevated mercury burdens in fish (Jones et al. 1986). Factors contributing to elevated mercury levels in these specific areas were not identified, but the potential influence of bedrock geology cannot be dismissed.

Some preliminary comparisons of fish mercury levels with sediment mercury levels have failed to establish a simple relationship between these two variables (e.g. McFarlane and Franzin 1980). However, many of those studies were based on a relatively small number of lakes. Bjorklund et al. (1984) reported a relationship between fish mercury burdens and surface sediment levels in Sweden. Hakonson (1980) developed a simple model to predict the mercury content of pike in Sweden based on surface sediment mercury content, water pH and a lake productivity index.

Detailed lake sediment geochemical data, including mercury, are available for areas of Ontario through the Geological Survey of Canada. These extensive sediment geochemistry data have not been previously applied to environmental studies. Since there has been, and continues to be, considerable interest and concern regarding mercury levels in Ontario fish, it seemed prudent to investigate the potential role of natural geological mercury levels in affecting mercury levels in fish. Shilts (1982) states that metal enrichment (in biota or sediments) in certain areas cannot be casually attributed to man's activities without knowledge of bedrock and sediment geochemistry.

2.0 PROPOSED WORK PROGRAM

The study was designed to investigate the relationship between mercury levels in sportfish, mercury levels in lake sediment (as an indicator of watershed geology) and lake water quality using data available from government files. Specific tasks were to:

1. Compile existing data from the Geological Survey of Canada on mercury content of lake sediments for lakes with available data on mercury in lake trout (listed in McMurtry 1986);
2. Using existing data on mercury in lake trout (Salvelinus namaycush) at standard length (McMurtry 1986), examine the relationships between mercury in sediment and mercury in lake trout using appropriate statistical techniques (e.g. correlation analysis, linear regression);
3. Using existing data on water quality and physical characteristics of lake trout lakes (McMurtry 1986), investigate relationships between mercury levels in standard length lake trout, mercury in sediments and lake characteristics;
4. Repeat the above 3 steps for lakes with available data on mercury in smallmouth bass (Micropterus dolomieu) (McMurtry 1987);
5. Repeat steps 1 and 2 only, for lakes with available data on mercury in brook trout (Salvelinus fontinalis), yellow perch (Perca flavescens) and walleye (Stizostedion vitreum) (MOE to provide data on mercury at standard length).
6. Prepare a report on the above work outlining data sources, methods used and results of analyses.

3.0 METHODS AND MATERIALS

3.1 Data Collection

3.1.1 Lake Sediment Geochemistry

Lake sediment geochemical data were obtained in the form of Open Files, on magnetic 9 track computer tape, from the GSC (Geological Survey of Canada), Energy Mines and Resources in Ottawa.

The GSC data were collected as part of reconnaissance surveys designed to gather a single index sample from a large number of lakes over a wide area. Both sediment and water samples are collected from each lake visited. The samples were collected under the auspices of the Uranium Reconnaissance Program (URP). In Ontario, there is a Canada-Ontario agreement on the URP. The data are shared between the GSC and Ontario Geological Survey, but the actual work and data analysis are all conducted by the GSC. The purpose of the data collection is to facilitate mineral exploration.

Individual sediment and water samples were collected from approximately 10,621 lakes under the URP in Ontario.

Sample collection, preparation and chemical analysis methods (Appendix 1) were consistent with the protocol developed and employed by the Exploration Geochemistry Subdivision of the GSC (D. Ellwood, pers. commun).

Lake sediment samples were collected from a helicopter during the open water period. Samples were collected from the deepest portion of the lake. The theory is that a midlake sample is the most representative of a watershed erosional product. Sample depths are included in the data set.

The sampling device used is referred to as a Hornbrook or GSC sediment sampler. It is cylindrical in shape with a cone-shaped nose. It is allowed to free-fall (but attached to a rope) from the water surface into the

sediments with the intent of obtaining a sample well below the sediment-water interface. The actual depth of penetration will largely depend upon the nature of the substrate. A "whistle" apparatus located about 2/3 the way up the cylinder allows for the very flocculent, organic matter, to be washed out of the cylinder as it is being retrieved. A one-way butterfly valve retains the sample in the cylinder.

The samples are air dried, ball milled, and the minus 80 mesh (180 microns) fraction obtained by GSC personnel. The subsequent samples are then sent out to independent laboratories for chemical analysis.

Each block of 20 samples contains 3 blind samples of either blanks, duplicates, or standard reference material submitted by the GSC for QA/QC purposes. The results of the QA/QC tests are statistically analyzed by a GSC scientist. Inspections of the field and analytical data are made to check for missing information or errors.

Analytical methodologies are available for 33 elements, but we will only report the technique for mercury.

Mercury was determined by the Hatch and Ott (1968) method with some modifications as described in the GSC protocol. A 0.5 gram sample was reacted with 20 ml concentrated HNO_3 and 1 ml concentrated HCl in a test tube for 10 minutes at room temperature prior to 2 hours of digestion with mixing at 90°C in a hot water bath. After digestion, the sample solutions were cooled and diluted to 100 ml with metal free water. The Hg present was reduced to the elemental state by the addition of 10 ml of W/V SnSO_4 in H_2SO_4 . The Hg cold vapour was then flushed by a stream of air into an absorption cell mounted in the light path of an AA spectrometer at a wave length of 253.7 nm.

The detection limit (DL) of the above technique was given as 10 ng/g. For reporting purposes, a value of 5 ng/g is assigned if the result is less than the detection limit.

The purpose of the GSC sampling technique is to obtain a measure of the natural mercury present in a watershed, not anthropogenic loading. This is desirable from our point since we also wanted a measure of geological or natural mercury loading for this project.

The areas covered by the GSC sediment sampling program are shown in Figure 1. Only those areas for which Hg data are available are highlighted. The actual area covered by the sampling program is as follows:

GSC Files 506, 507, : 27,700 km²

GSC Files 899,900, : 38,054 km²

GSC Files 1356,1357 : 16,750 km²

Sediment mercury data is available for 6,715 samples. This includes a number of duplicates, so the actual number of sites sampled for mercury is approximately 6,314.

The total number of variables from the GSC survey are listed in Table 1. Both sediment and water chemistry variables are given to indicate the nature of the available database. For example, in GSC Open File 899 and 900, for each sample location there are 28 sediment variables, 19 water chemistry parameters, and 7 physical measurements for a total of 54 records at each site.

Detailed maps (blueprints) were obtained showing the location of each GSC sample site, with individual maps for each sediment and water parameter showing the value of each variable (e.g. Hg, pH) at that sample location.

The separate Open Files were loaded onto the HP 1000 mini computer at Markham Data and stored as a single large file.

3.1.2 Fish Mercury Data and Provincial Water Quality Data

The Ontario Ministry of the Environment and the Ontario Ministry of Natural Resources have jointly developed databases incorporating mercury levels at a standard fish length, lake physical characteristics and water quality data for a number of lakes in Ontario. Databases were available for smallmouth bass, lake trout, and later in this study, for walleye. Mercury levels at standard length were available for the following number of lakes for the individual species:

Smallmouth bass :	91
Lake trout :	91
Walleye :	255

All mercury concentrations in fish tissue were analyzed by the Ontario Ministry of the Environment (OME 1981).

Individual lakes were chosen on the basis that at least 10 fish were sampled for mercury from that lake, and that there was a statistically significant correlation ($p < 0.05$) between log mercury and total fish length (McMurtry 1986). To compare mercury levels between lakes without a length bias, the average mercury concentration was predicted for a hypothetical fish of a standard length. The following standard lengths were utilized for the three species:

Smallmouth bass:	31 cm
Lake trout :	44 cm
Walleye :	41 cm

Mercury levels at standard length were not available during the term of this project for yellow perch or brook trout as indicated in Task 5 of the proposed work plan. However, in addition to only relating mercury levels in walleye to sediment mercury concentrations (as outlined in Task 5), we also examined walleye mercury levels in relation to water quality.

Water quality data from the Provincial Acid Sensitivity database were incorporated with the fish mercury data set. Water quality information for this database was gathered from a variety of sources (McMurtry 1986). To differentiate between water quality values from the GSC and provincial databases, the provincial variables were given the prefix "MNR", while the GSC data were given the prefix "Aq". For example, MNR-pH and Aq-pH would indicate pH values from the provincial and GSC databases, respectively. Sediment variables were all provided by the GSC, and were given the prefix "sed". A full data listing for each variable is provided in Appendix 2.

3.2 Merging GSC and Provincial Databases

The first step in the merging process was to identify lakes for which there existed overlapping GSC sediment and water quality data, and provincial fish mercury and water quality data.

To merge the GSC and MOE/MNR data a common location system had to be employed. Sample locations for the fisheries data are given in latitude and longitude in degrees and minutes. Since one minute of latitude equals 1852 meters, this is the closest approximation to the fisheries sample site possible.

The GSC sample location is given by the UTM (Universal Transverse Mercator) coordinates which is close to within 100 meters. A formula was employed to convert the Lat/Long. coordinates to UTM.

For example: Conversion of the MOE/MNR lat/long for Big Porcupine Lake gave the following UTM coordinates.

Converted = 686372 5035487

GSC sample = 685874 5035532

This places the location of the GSC sample site and the fisheries sample within 500 meters of each other.

Since the two coordinates will not match exactly, a program was used to find the number of data matches within a 5 km radius. Each of these steps was employed separately for the three individual fish species. However, we will discuss the process in general terms which covers each species. Some refinement was required since there was a potential error that a match would be made when the GSC did not sample from the actual waterbody where the fish were obtained, but from another waterbody within 5 km.

If the match distance was narrowed too much, e.g. less than 1 km, a second type of error was incurred; that a legitimate pair of data would be missed. For example, the closest match distance in Bear Lake was 1,148 m, but none of the samples were from within the lake. Conversely, the closest match distances in Muskoka and Clearwater lakes were 1,701 and 1,183 m, respectively. Yet the GSC sampled directly from these waters. Thus, a criteria of using only potential matches less than 1 km would have missed these actual direct matches.

To avoid missing any matches, or making matches where overlap actually did not exist, we consulted the sample location maps for each lake showing potential matches less than 5 km. In this way we confirmed each potential match to check if the GSC collected a sediment sample from that lake for which fisheries data were available.

In some cases the match distances were much lower, yet the sample locations were also checked by hand. For example:

Big Porcupine	= 500 m
Esten	= 100 m

We also examined the potential to take advantage of the "oversampling" on the part of the GSC, and calculated an average of all sediment mercury values within a 5 km radius. This value was then compared to the actual lake sediment mercury concentration.

3.3 Comparison of GSC and Provincial Water Quality Data

Water quality data for the study lakes were available from both the GSC and provincial databases. The original intent of the study was to integrate sediment mercury data with the provincial water quality database. However, as the study progressed it was apparent that in many cases the GSC database was more complete than the provincial database. This was especially true for the walleye lakes for which very little provincial water quality data were available. The actual number of lakes with data for a particular water quality variable is presented in the summary statistics; Table 6 (Smallmouth bass), Table 8 (Lake trout) and Table 10 (Walleye).

We wanted to take advantage of the GSC water quality data for statistical purposes to increase sample size wherever possible. However, before utilizing the GSC values we screened the data for accuracy and compatibility with the provincial water quality database. To do this data were obtained from lakes which both the GSC and province had sampled. Values for the same water quality parameter (eg. pH) were statistically compared using Pearson correlation coefficients. If there was a good correlation ($p < 0.05$) between the GSC and provincial values we examined the relationship using simple linear regression and plotted the data on a graph. If the slope of the regression of GSC water quality data on MNR water quality data was close to 1.0, we used the GSC data in addition to the provincial water quality data for statistical purposes.

3.4 Interspecies Standardized Mercury Correlations

During the course of the data merging, it was apparent that for a number of lakes, standardized fish mercury concentrations were available for more than one species. Where the distribution of smallmouth bass, lake trout and walleye overlapped, we examined the correlation between standard mercury concentrations for different species among lakes. Not all the overlapping

lakes for fish species corresponded to lakes with sediment geochemistry data. This was not considered a constraint, however, as this examination was not in the proposed work plan, and was secondary to the main objectives of the research.

Standardized fish mercury levels were available on the following combination of overlapping lakes:

- Smallmouth bass - walleye
- Smallmouth bass - lake trout
- Walleye - lake trout

3.5 Data Analysis

Although the results are reported separately for each of the 3 fish species, the statistical analyses and data treatment were the same in each case.

The merged data sets were stored on the HP-1000 mini computer at Markham Data Incorporated. For each lake we recorded lake name, location, standardized fish mercury concentration, GSC sediment geochemical values, GSC water quality values, MNR physical lake values (e.g. lake area, maximum and mean depth) and MNR water quality values. In addition to lake name, location and fish mercury, each lake record consisted of a possible 74 numeric values: 37 GSC sediment parameters, 20 GSC water quality parameters, and a possible 17 MNR physical and water quality parameters. Records for individual lakes were generally incomplete in that there were many missing values among the MNR parameters. A complete data list for each lake is provided in Appendix 2. Where, Appendix 2-A consists of the data list for smallmouth bass lakes, 2-B contains lake trout data, and walleye data is in Appendix 2-C.

Preliminary data analyses were conducted on the HP-1000 using the Log II software program and GEOCHEM statistics module. In the GSC data, a value of one half the detection limit is used for statistical purposes if a sample is

below the measurable detectable limit for a specific element or chemical. Summary statistics were prepared for all lake variables plus fish mercury concentration. Correlation matrices were prepared as a first step in examining the relationship between fish mercury level at standard length with lake sediment or water quality variables. Summary statistics and preliminary correlation matrices are presented in Appendix 3. Since the GEOCHEM software module accepts a maximum of 10 variables at a time for correlation analysis, the data are summarized in groups of 10 or less variables, with each group containing the standardized fish mercury data.

The correlation matrices were examined with the purpose of reducing the number of independent variables below 74. Variables were dropped from further statistical analysis if there was no significant correlation ($p > 0.05$) with standardized fish mercury. The rationale for dropping other variables was sometimes more subjective and based on interpretation. If a significant correlation between fish mercury and a sediment variable had no rationale or ecological explanation, it was removed from further statistical treatment.

The reduced data sets were transferred or "downloaded" onto floppy diskettes for further analysis on IBM-compatible personal computers. Summary statistics, Pearson correlation coefficients, residuals and stepwise multiple regression analysis were conducted using SPSS/PC+.

The Pearson correlation coefficient (r) measures the relationship between two variables. A quantitative measure of the predictive value of the correlation coefficient is given as r^2 .

The \log_{10} of standardized fish mercury was used as the independent variable for all regression analysis. Some water quality variables were transformed for regression analysis as described by McMurtry (1986). Residuals of the regression \log_{10} fish mercury (LI0-FISH) against sediment mercury (SEDHG) were examined for homogeneity of variance and normality. The standardized residual plots of sediment mercury concentrations were normal (Appendix 4) so sediment mercury was not transformed.

The drainage area/lake volume ratio was defined as terrestrial watershed area (WAREA) plus lake area (LAREA) divided by lake volume (VOL).

Subsets of lake variables were entered as independent variables in the stepwise regression analysis since the reduced fish data sets still consisted of up to 31 independent variables. Specific data subsets included a) sediment chemical variables only, b) MNR water quality data only, c) GSC water quality data only, and d) a combination of GSC and/or MNR water quality data and sediment mercury (SEDHG) concentration.

Entering subsets of independent variables reduced two fundamental problems in multiple regression analysis: a) multicollinearity, and b) missing values. Multicollinearity refers to highly correlated independent variables (e.g. often pH, alkalinity. The first suggestion that some of the independent variables may be correlated is provided in the preliminary correlation matrices. Multicollinearity is also automatically checked in the SPSS/PC+ REGRESSION procedure by the TOLERANCE criteria (SPSS/PC+ Manual 1986). Entering too many correlated independent variables reduces the tolerance of other variables, with the ultimate problem that no variables will be accepted in the equation.

Problems of missing data values arose when attempting to combine MNR water quality and sediment mercury values. We assumed that data values were missing randomly. In some instances, the same variable was missing for most lakes (e.g. MNR-colour in smallmouth bass lakes). Variables with consistently missing values were omitted from regression analysis. Other missing data values were treated by one of two methods. One alternative is to keep all variables but eliminate the cases with missing values in any of them. This is termed LISTWISE missing-value treatment since a case is eliminated if it has a missing value on any variable in the list.

Problems arise if many cases have missing data for some variables, then the LISTWISE treatment could eliminate too many cases and result in a very small sample size. The alternative technique is to calculate the correlation

coefficient between a pair of variables based on all cases with complete information for those two variables, regardless of whether the cases have missing data on any other variable. This is called PAIRWISE missing-value treatment. We primarily employed PAIRWISE treatment to maximize sample size (degrees of freedom) within the regression equation.

In regression analysis it is important to remember that a strong association between variables does not necessarily prove or even imply that the independent variables are causes of the dependent variable. To make causal inferences additional methodology and experimentation are required (Kleinbaum and Kupper 1978). Furthermore, it is often a good idea to develop several acceptable regression models, and then choose among them based on interpretability, ease of variable data acquisition and so forth (SPSS/PC+ manual).

4. RESULTS

4.1 Sediment Mercury Data

In many cases more than one sediment sample was collected from within a lake (e.g. Lake Muskoka, N = 9). The mercury concentration used for statistical purposes was the average of all samples collected within a lake. The variability of mercury levels among samples collected within a lake was small. Table 2 summarizes the standard deviation and range of sediment mercury concentrations in lakes where three or more sediment samples were collected. Tables 3 to 5 summarize the average sediment mercury concentration within the study lakes.

Tables 3 to 5 also include the average mercury concentrations for all sediments sampled within 5 km radius of the lake coordinates from fish data. This value is referred to as the 5 km average sediment value.

There appeared to be a good correlation between the actual and 5 km average sediment mercury concentrations (Figure 2). However, no further statistical

comparisons were made between these two values since only the actual average mercury concentration was used for statistical purposes in this study. The average sediment mercury concentrations in smallmouth bass, lake trout and walleye lakes were 99, 88 and 138 ng/g, respectively (Tables 3 to 5). The total range of sediment mercury levels among all lakes was 5 to 1000 ng/g.

Sediment mercury concentration was negatively correlated with lake pH within the smallmouth bass lakes ($r^2 = -0.42$, $p < 0.01$), but was not correlated with water pH in walleye or lake trout lakes (see Appendix 5 for details).

4.2 Merged GSC and Provincial Data bases

Using the existing criteria of potential fish/sediment matches within 5 km, the following number of data pairs were obtained:

Walleye = 55/255
Lake trout = 48/91
Smallmouth = 73/91

After consulting the maps, the following number of actual direct sediment-to-fisheries matches were obtained:

Walleye - 44 lakes
Lake trout - 42 lakes
Smallmouth bass - 66 lakes

The individual fish mercury concentrations at standard length and sediment mercury concentration for each lake are presented by species in Tables 3 to 5.

4.3 Comparison of GSC and Provincial Water Quality Data

There was very good correlation ($p < 0.05$) between water quality values for overlapping lakes in the GSC and Provincial databases. For example, the correlation coefficient (r) between GSC-pH and MNR-pH within smallmouth bass lakes is 0.88 (Figure 3a). The Pearson correlation coefficients for all overlapping water quality variables are presented in Appendices 3 and 5.

The relationships between GSC and MNR/MOE data values for water pH, alkalinity, conductivity, sulphate and calcium in overlapping smallmouth bass lakes are illustrated in Figures 3a to 3f. Alkalinity values were compared over the full range of lake conditions (Figure 3d), in addition to lakes with alkalinity < 10 mg/l (Figure 3e). It was felt that the potential for measurement error was greater in lakes with alkalinity < 10 mg/l, and this division would be a better test of the accuracy of the two respective databases.

The relationships between GSC and the provincial data values for pH and alkalinity for smallmouth bass lakes are described by the following simple linear regression equations:

$$\text{GSC-pH} = 0.90 \text{ MNR-pH} + 0.398, \quad r = 0.88, \quad n = 55$$

$$\text{GSC-alk} = 0.96 \text{ MNR-alk} - 0.042, \quad r = 0.99, \quad n = 54$$

A slope close to 1 suggests the data are not just linearly correlated, but the values for individual lake from the two databases are very similar. This would be expected for conservative variables such as conductivity and alkalinity, but the similarity between pH values is surprising given the temporal fluctuations of pH within a single waterbody.

Based on the high correlation between the GSC and Provincial water quality data, both databases were utilized for multiple linear regression analyses of fish mercury relative to lake variables. Preference was given to GSC data to

maximize sample sizes for each variable. However, as will be seen, the end result of the multiple regression analyses was not affected by the source of water quality data used.

4.4 Relationship of fish mercury levels with lake variables.

4.4.1 Smallmouth bass

A total of 66 lakes were selected on the basis of having available standardized fish mercury concentration, sediment mercury levels and other sediment and water quality data.

The overall mean standardized fish mercury concentration for a 31 cm bass was 402 ng/g (range 132-943 ng/g, Table 6). The mean GSC pH of these lakes was 6.97 (range 5.6-8.2) compared with a mean MNR/OME pH of 7.21 (range 5.99-8.58). The mean GSC alkalinity was 33.9 mg/L. The mean sediment mercury concentration was 99 ng/g (range 5-180 ng/g).

The standardized log fish mercury (LIO-FISH) concentration was significantly correlated with a number of sediment and water quality variables (Appendix 5) and summarized in Table 7. Fish mercury was positively correlated with sediment mercury concentrations ($r = 0.31$, Figure 4), and negatively correlated with sediment sulphur ($r = -0.38$) and loss on ignition ($r = -0.26$). The greatest simple correlation with a water quality variable was with MNR-Fe ($r = 0.72$), MNR-Mg ($r = -0.55$), pH ($r = -0.52$, GSC or MNR) and Aq-Cond ($r = -0.50$). It should be noted that the number of lakes with MNR-Fe was only 9, compared with $N > 55$ for the other major correlated variables. Figure 5 illustrates the correlation between lake pH and standardized mercury concentration in smallmouth bass.

Many of the water quality (ionic) variables were highly inter-correlated. The correlation coefficients among all independent lake variables are presented in Appendix 5. Sediment mercury concentrations were positively correlated with sediment organic carbon ($r = 0.32$) and loss on ignition ($r = 0.30$), and

negatively correlated with some water quality variables including Aq-pH ($r = -0.42$), and Aq-Alk ($r = -0.48$) and MNR-Ca ($r = -0.54$). The variable C-ORG is equivalent to DOC.

The mean FISH-HG in lakes with $\text{pH} \geq 6.5$ was 353 ng/g ($n = 49$), compared with 545 ng/g in lakes with $\text{pH} < 6.5$ ($n = 17$).

The results of stepwise multiple linear regression analyses for different subsets of independent variables are summarized below. The groups of independent variable subsets presented here is only a small representation of the variable combinations analyzed. It does represent a succinct list of combinations dividing MNR and GSC water quality data entered separately and in combination with sediment mercury. It must be noted that the exact results of regression procedures will vary depending on the subset of variables entered.

Log10 fish mercury was always the dependent variable entered.

1) Independent variables entered: Inv-MNR-Ca, MNR-pH, L10-Larea, MNR-Corg (NB. Corg = DOC)

Independent Variable	Slope	Partial R sq	F	P
Inv-MNR-Ca	0.993	0.337	20.8	0.000
MNR-Corg	0.042	0.064	13.4	0.000

N = 43, Model $R^2 = 0.401$, Constant = 2.18

(Note N = 43 since MNR-Corg data were available for only 43 smallmouth bass lakes).

When sediment mercury (Sed-Hg) was added to the above set of MNR independent variables the regression results remained the same. In other words, Sed-Hg was not chosen as a significant independent variable.

2) Other MNR independent variables entered: MNR-pH, L10-Larea, MNR-Corg, Sed-Hg, Inv-MNR-Ca, MNR-SO4, MNR-Alk, MNR-Cond, MNR-Mg.

Independent Variable	Slope	Partial R sq	F	P
Inv-MNR-Ca	0.706	0.337	20.4	0.000
MNR-SO4	-0.035	0.079	13.9	0.000

N = 42, Model R^2 = 0.416, Constant = 2.69

3) GSC water quality and sediment mercury: Aq-pH, L10-Larea, Sed- Hg, Inv-Aq-Ca, Aq-SO4, Aq-Alk, Aq-Cond.

Independent Variable	Slope	Partial R sq	F	P
Inv-Aq-Ca	0.86	0.35	32.88	0.000

N= 62, Constant = 2.41

4) Combination of GSC and MNR water quality variables: Aq-pH, L10-Larea, MNR-Corg, Sed-Hg.

Independent Variable	Slope	Partial R sq	F	P
Aq-pH	- 0.146	0.27	15.2	0.00
N = 43, Constant = 3.58				

5) as number 4 plus Inv-Aq-Ca

Independent Variable	Slope	Partial R sq	F	P
Inv-Aq-Ca	0.973	0.35	22.1	0.000
MNR-Corg	0.042	0.06	14.0	0.000
N = 43, Model R ² = 0.41, Constant = 2.21				

Sediment mercury concentration (Sed-Hg) was not selected as a predictor of fish mercury in any reduced data set during multiple linear regression.

4.4.2 Lake Trout

The mean standardized mercury concentration in sampled lake trout was 303 ng/g ($n = 41$ lakes, range = 70 - 1033 ng/g). Limerick lake was omitted for statistical purposes from the original 42 lake trout lakes because the extremely high alkalinity and conductivity of this lake (Appendix 2-B) classified these values as outliers and disproportionately influenced statistical correlations.

The mean sediment mercury concentration in lake trout lakes was 138 ng/g (Table 8).

The mean GSC-pH was 6.4, compared with a mean MNR-pH of 6.6. The average pH of sampled lake trout lakes was substantially lower than the average pH of either smallmouth bass or walleye lakes.

Fish mercury concentration was not significantly correlated ($p > 0.05$) with lake pH ($r = 0.24$) or sediment mercury concentration ($r = -0.10$). The relationship between mercury concentration in lake trout and sediment mercury concentration is illustrated in Figure 6.

Fish mercury concentration was correlated with log lake area (LAREA), where $r = 0.57$, and dissolved organic carbon (MNR-Corg), where $r = 0.43$. Significant correlations between lake trout standard mercury concentration and lake variables are summarized in Table 9.

Sediment mercury concentration was correlated with water colour (MNR-colour), where $r = 0.60$, $p = 0.003$.

A number of data subsets were entered for stepwise multiple regression analysis. A summary of the results of three subsets are presented.

1) Independent variables entered: L10-Area, MNR-Corg, MNR-pH, MNR-SO4, Inv-Ca, Sed-Hg,

Independent Variable	Slope	Partial R ²	F	P
MNR-Corg	0.112	0.28	10.4	0.003
L10-AREA	5.1E-5	0.14	9.5	0.001

Constant = 2.015, Multiple R² = 0.42, n = 29

There were only 29 lake trout lakes with MNR-Corg. Lake pH or sediment mercury were never selected as predictor variables in multiple regression analysis.

2) MNR water quality data and Sed-Hg entered: L10-Larea, MNR-Corg, MNR-pH, MNR-Alk, Inv-Cond, Inv-Ca, L10-Mg, MNR-SO4, Sed-Hg.

Independent Variable	Slope	Partial R ²	F	P
MNR-Corg	.089	0.2778	10.4	0.003
L10-Larea	.179	0.131	9.0	0.001

N = 29, Constant = 1.695, Model R² = 0.41

3) Entering GSC water quality variables plus log lake area and sediment mercury: Sed-Hg, LI0-Larea, Aq-pH, Aq-Na, Aq-Alk,

Independent Variable	Slope	Partial R ²	F	P
LI0-Larea	0.23	0.257	12.1	0.001

N = 39, Constant = 1.83, Model R² = 0.257.

Log lake area and dissolved organic carbon were selected as the two best combined predictors of fish mercury concentration. Lake pH or sediment mercury were not chosen as predictors of mercury levels in standard length lake trout.

4.4.3 Walleye

The mean standardized mercury concentration in walleye was 517 ng/g (n= 44 lakes, range = 128-2216, Table 10). The mean sediment mercury concentration was 88 ng/g (range 10-188).

The average GSC and MNR pH of the walleye lakes were 7.32 and 7.28, respectively. The average pH was similar to smallmouth bass lakes but the range was not as great. For example, only 2 of the 44 walleye lakes had pH < 6.5.

Log fish mercury concentration was correlated with sediment mercury concentration ($r = 0.34$, $p = 0.013$), GSC-pH ($r = -0.28$, $p = 0.03$),

GSC-SO4 ($r = -0.45$, $p = 0.007$), GSC-Alk ($r = -0.51$, $p = 0.000$), and GSC-Cond ($r = -0.57$, $p = 0.001$). Table 11 summarizes the significant correlations of fish mercury with lake variables. The relationships between standardized walleye mercury concentration and sediment mercury concentration is illustrated in Figures 7.

Fish mercury concentration generally did not correlate with any of the provincial water quality variables. This is attributed to the limited availability of provincial water quality data for walleye lakes.

Stepwise multiple linear regression analysis consistently chose conductivity (Aq-Cond) as the single best predictor of log fish mercury concentration, as described by the equation:

$$L10-FISH = -0.002(Aq-Cond) + 2.88, \quad r^2 = -0.32, \quad n = 30.$$

$$F = 13.4, \quad p = 0.001$$

Other variables entered and not selected included: Mean-dep, Sed-Hg, Aq-SO4, Aq-Corg. GSC alkalinity or calcium could also be used in place of conductivity to provide regression equations with slightly lower r^2 values.

4.5 Interspecies Correlations

Standardized fish mercury concentrations were available for the following number of overlapping lakes:

Smallmouth bass - walleye: 27 lakes

Smallmouth bass -Lake Trout: 13 lakes

Lake Trout - walleye: 6 lakes

There was a good correlation of standard mercury concentrations between species among overlapping lakes. Figures 8 and 9 illustrate the relationships

between smallmouth bass - walleye mercury and smallmouth bass - lake trout mercury, respectively. The relationship of standardized mercury levels between lake trout and walleye was not analyzed due to the small sample size available in the database.

5.0 DISCUSSION

The results indicate that background sediment mercury levels were significantly correlated with mercury levels in smallmouth bass and walleye. However, the background sediment mercury levels did not explain the differences observed in fish mercury levels between lakes.

An important aspect of this study was the fact that "deep" sediment mercury concentrations were used as an indicator of geological mercury levels. Other studies have established that background mercury levels in lake sediments are generally lower than surface sediment mercury concentrations (Evans 1986; Johnson et al 1986; Johnson 1987).

There is increasing evidence that atmospheric deposition may be a significant source of mercury to remote lakes. Galloway et al (1982) estimated that anthropogenic emissions of mercury to the atmosphere exceed natural emissions by 275 times. On a global basis, this "mobilization factor" for metals and trace elements was exceeded only by lead.

Glass et al (1986) found that mercury concentrations in precipitation and in lake water from precipitation-dominated lakes were similar, and concluded that atmospheric deposition can be the major source of mercury to lakes in the Lake Superior region. Other studies have used sediment core mercury profiles as an index of mercury loading through time. This method has revealed increased mercury loading since the turn of the century in the Turkey Lakes (Johnson et al 1986) and in other regions of south-central Ontario (Evans 1986).

The average background sediment mercury level in this study was 99 ng/g in smallmouth bass lakes, 138 ng/g in lake trout lakes and 88 ng/g in walleye lakes. These values agree very closely with other studies that suggest the background mercury concentration in lake sediments is approximately 100 ng/g (Forstner and Whittman 1981; Cahill and Shimp 1984; Bjorklund et al 1984; Evans 1986).

In a study of mercury in the Turkey Lakes, Johnson et al (1986) found that surface sediment levels were approximately 2.72 times greater than mercury levels in deeper sediments. When the actual rate of sedimentation was taken into account, it was calculated that anthropogenic loading of mercury was 1.4 times background loading.

Evans (1986) reported that mercury levels in surface sediments (0-2 cm) were 2 to 4 times greater than background levels. It is interesting to note that in the latter study, surface sediment mercury levels were much lower in lakes with higher alkalinity, and not located on the Precambrian Shield. Johnson (1987) noted that mass sedimentation rates were significantly greater in softwater Precambrian shield lakes than in hardwater lakes. The differences must be related to morphometric and physical factors, which could also influence relative loading rates of mercury from the watersheds between areas.

Evans (1986) found no relationship between the ratio of drainage area: lake area and natural mercury loading. He suggests this indicates there is a significant transport of anthropogenically derived mercury from the watersheds into the lake, a concept used with other metals (Dillon and Evans 1982).

Johnson (1987) suggests that precipitation loading can account for anthropogenic loading of mercury in lake sediments in Ontario. Furthermore, he found a strong correlation between mercury loading rates (a combination of anthropogenic and natural inputs) and mercury concentration in a variety of fish species in Ontario lakes. Suns et al (1987) also report a positive correlation between potential mercury loading (using drainage area:lake volume ratio) and mercury levels in yellow perch. Evans (1986) suggests that the

ratio of drainage area:lake area provides an index of mercury burdens in lake surficial sediments.

It may not be possible to derive a simple variable based on lake morphometric conditions (eg. drainage area:lake volume) that would provide a reliable estimate of total mercury mercury in fish. Fish mercury levels are more likely influenced by a number of factors, acting simultaneously, relating to availability and loading rate. The factors regulating mercury loading to a lake including precipitation amount, sedimentation rate, weathering and runoff within a catchment can vary significantly between watersheds. The loading integrates natural and anthropogenic mercury input. Under current geochemical cycling regimes, anthropogenic loading will likely dominate.

The results of this study and those of Johnson (1987) and Bjorklund (1984) suggest that surface sediment mercury concentrations may be better than background sediment levels as an indicator of mercury availability, and fish mercury levels within a lake. However, since other factors such as water quality have an obvious influence on fish mercury levels, it is becoming apparent that fish mercury levels cannot be accurately predicted by a single environmental variable.

The lake variables correlated with mercury levels at standard length in smallmouth bass and walleye were similar. For example, the correlation between fish mercury and sediment mercury in these two species was approximately 0.30. The high correlation between standard mercury levels in smallmouth bass and walleye among lakes also suggests that the same variables are influencing mercury uptake in these species.

Dissolved organic carbon was also selected as an important predictor of mercury levels in smallmouth bass. The significance of this variable in relation to mercury uptake will be discussed in more detail below in conjunction with lake trout.

Mercury levels in smallmouth bass and walleye were highly correlated with variables reflecting water hardness and acidity. Calcium and conductivity were generally better single predictors of fish mercury than lake pH. This may be partially attributed to the quality and variability of lake pH data, and also to greater direct influence of calcium than pH on mercury uptake.

Water hardness and lake pH likely influence mercury uptake and availability simultaneously within a lake. Rodgers and Beamish (1983) reported that the efficiency of methyl mercury uptake by rainbow trout was much greater in softwater (30 mg/l as CaCO₃) compared with hardwater (385 mg/l as CaCO₃). The mechanisms to account for this effect may be increased gill permeability at low Ca levels (Spry et al 1981) or competition between metals and Ca for cellular binding sites (Zitko and Carson 1976).

Reduced lake pH may increase the bioavailability of mercury by stimulating bacterial methylation from the sediments (Xun et al 1987). Thus, a combination of increased production and uptake efficiency could explain elevated mercury levels in fish from low pH lakes.

Figure 5 suggests that mercury levels in smallmouth bass have little correlation with lake pH above pH of 7.0. Similarly, McMurtry (1986) found that dissolved organic carbon influenced mercury levels in lake trout, but only up to a critical value, above which there was no effect.

Negative correlations between lake pH and/or alkalinity and mercury content of fish in Ontario have now been demonstrated for yearling yellow perch (Suns et al 1980), pumpkinseed sunfish (Wren and MacCrimmon 1983), smallmouth bass (McMurtry 1987; Suns et al 1987) and now walleye (this study). Of these, the walleye lakes had the greatest geographical distribution in the province.

Mercury concentrations in standard length lake trout were highly correlated to DOC and lake area, but not water hardness or acidity variables. Dissolved organic carbon was also selected in conjunction with calcium as predictors of mercury levels in smallmouth bass. Mercury in smallmouth bass was highly

correlated to water iron levels, but the sample size was relatively small (n=9). Iron is often associated with lake dystrophy and humic material. Studies in Sweden and Finland have also noted a positive correlation between fish mercury levels and the humic content of water (Verta 1984; 1985; Lindqvist et al 1986). It is suggested that the humic substances act as both an energy source and source of mercury for the methylating bacteria (Verta 1985). Bodaly and Hecky (1984) suggest that increased availability of organic material accounts for elevated fish mercury levels in new hydroelectric reservoirs.

Biological conditions (eg. growth rates, food chain structure) can also influence mercury uptake by a fish species. It is possible that biological variables are influencing mercury uptake in lake trout to a greater extent than in the other two species, and are over-riding the influence of either pH or water hardness. It is well established that the growth rate of lake trout in Ontario lakes is strongly influenced by diet (Martin 1966). Differences in lake trout growth rate are apparent if the diet is primarily planktivorous or piscivorous. Even among piscivorous populations, there may be differences if the food base is comprised of yellow perch, smelt or ciscoe.

The mercury content of different prey items will also differ, and affect mercury transfer rates to the lake trout. For example, MacCrimmon et al (1983) noted a seven fold increase in lake trout mercury levels when a population changed from a planktivorous diet, to a diet largely composed of smelt. Bjorklund et al (1984) noted an increase in mercury levels in northern pike when they switched from a diet of yellow perch to roach. In the latter example, the change in diet was brought about by altered community structure due to lake acidification. Thus, lowered pH affected mercury uptake in the pike through both stimulated bacterial production and altered food base.

The diet of smallmouth bass and walleye may be more consistent between lakes, and not have as great an influence on dietary transfer of mercury to these species. It would be possible to test this hypothesis by obtaining information on the nature of the principal prey items in the individual lake trout lakes,

and compare standardized mercury levels using food items as an independent variable.

It is notable that the average mercury concentration in a 41 cm walleye (517 ng/g) is above the recommended safe level of mercury in fish for unlimited consumption. A length of 41 cm corresponds to the average length of walleye sampled in the sportfish contaminant monitoring program (Scheider pers commun).

The demonstrated relationship of mercury concentrations between species is significant. This is the first study to document a relationship between mercury levels in sportfish from such a large number of lakes. A relationship between mercury levels in different fish species has great potential as a management tool both for predicting mercury levels in other species, and for designing fish contaminant monitoring programs.

This study demonstrates the value of utilizing existing databases for environmental research. In this case the GSC geochemistry data for mineral exploration was invaluable in providing sediment mercury data. The full value and potential of the GSC water quality data has yet to be assessed. Databases created for other purposes or other disciplines can be effectively utilized at a fraction of the time and cost in conducting similar surveys.

There is increasing evidence to suggest that atmospheric deposition has elevated surficial sediment mercury levels in Ontario lakes. The relationship between surface sediment mercury levels and mercury levels in fish should be investigated.

There is increasing empirical evidence to suggest that dissolved organic carbon is linked to mercury levels in fish. DOC has an important role in the geochemical cycling of many other metals (Forstner and Whittman 1981). The importance of DOC in influencing the biological availability of mercury in Ontario lakes should be investigated.

The results of this study indicate that background sediment mercury levels do not account for the observed differences in mercury levels in fish between lakes. The differences may be explained by water quality, especially DOC, pH and alkalinity. Therefore, the factors and conditions affecting these variables in Ontario lakes will also influence mercury availability and uptake in fish. Experimental studies, or more controlled field collections are required to elucidate the causal relationships and mechanisms involved. These variables will act simultaneously on mercury uptake and availability, and the net effect from individual variables will differ between species and lakes.

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TABLE I

SUMMARY OF GEOCHEMISTRY DATA

Ontario = # samples = 10,621

GSC File #	Survey Year	Map Nos.	Sediment Variables	Water Variables
-----	-----	-----	-----	-----
506	1978	52A	Zn, Cu	U, F, pH
507		52H (S 1/2)	Pb, Ni	
(colour maps		42D	Co, Ag	
= File 746)		42E (S 1/2)	Mn, As	
		42C	Mo, Fe	
Thunder Bay		42F (S 1/2)	U, LOI	
		41N	Hg	
		41K (N 1/2)		
899	1976	31C (N 1/2)	Zn, Cu, Pb	U, F, pH
(map = 747)	1982	31F	Ni, Co, Ag	Zn, Mn, Fe
			Mn, As, LOI	Na, K, Ca, Mg
Kingston			U, CO ₂ , C, S	C, Cl, Br, NO ₃
			Rb, Sr, Cr, Zr	SO ₄ , PO ₄
			SiO ₂ , AlO ₂	CaCO ₃ , O ₂
			CaO, MgO	Cond.
			Na ₂ O, K ₂ O	
			MnO, P ₂ O ₅	
			TiO ₂ , BaO	
			Hg	
900	1982	31D (S 1/2)	As above plus	As 899
		31E (N 1/2)	V, Cd	
Huntsville		41H (E 1/4)		
1356	1986	41J		
1357	1986	41O	Zn, Cu, Pb	V, F, pH
			Ni, Co, Ag	Ca, Mg
Chapleau			Mn, As, Mo	CaCO ₃
			Fe, U, LOI	
			F, V, Cd	
			Au, Sb, Hg	

Other data:

- location
- lake area
- rock type
- sample depth
- replicate status
- sample colour
- suspended matter

Table 2. Mean, standard deviation (SD) and ranges of sediment mercury concentrations (ng/g) within study lakes where more than three sediment samples were collected.

Lake Name	N	Mean (ng/g)	SD	Range
<u>Smallmouth Bass lakes</u>				
Balsam	5	80	31	40 - 120
Buckhorn	3	73	47	20 - 90
Cameron	4	75	15	50 - 80
Four Mile	3	93	32	50 - 110
Jack	3	107	12	100 - 120
Kashe	3	127	42	70 - 160
Kasshabog	5	76	34	50 - 130
L. Clear	3	13	26	10 - 60
L. Dore	3	70	20	50 - 90
Limerick	3	50	17	40 - 70
Lower Buckhorn	7	77	24	60 - 130
Matinenda	5	110	45	45 - 158
Muskoka	9	89	31	50 - 120
Pike	3	50	17	40 - 70
Six Mile	3	123	64	50 - 160
Steenburg	3	107	38	80 - 150
Stony	5	134	34	80 - 160
Upper Rideau	3	38	38	5 - 80
<u>Walleye lakes</u>				
Calabogie	3	127	32	90 - 150
Canal	4	95	25	70 - 130
Crotch	3	70	17	50 - 80
Golden	3	60	26	30 - 80
Kashwakamak	4	90	0	90 - 90
Round	5	62	27	20 - 90
Skootamatta	4	162	51	190 - 220
Trapnarrows	4	120	30	90 - 150
Windemere	6	67	64	30 - 140

NB. All Lake Trout lakes with three or more sediment samples are represented in smallmouth or walleye data sets.

TABLE 3. Summary of standardized mercury concentration and sediment mercury levels in smallmouth bass lakes.

SMALLMOUTH BASS LAKES

Lake Name	Actual Sediment [Hg](ppb)	Actual N	Average Sed [Hg] < 5 Km	Average N	Stand. Fish [Hg](ppb)
Arrowhead	110	1	103	3	275
Balsam	80	5	80	5	151
Bass	50	1	50	1	132
Bay	100	1	138	4	597
Big Mink	160	1	137	6	552
Buckhorn	73	3	73	3	186
Buckshot	95	2	110	6	339
Cameron	75	4	70	5	323
Crosby	70	1	65	4	373
Dickie	130	1	130	5	593
Drag	110	2	131	7	400
Faraday	130	1	112	5	298
Farrel	80	1	68	4	269
Four Mile	93	3	83	4	200
Fox	130	1	150	6	743
Fraser	10	2	48	5	355
Gull	70	2	108	6	336
Haines	170	1	155	8	763
Head	100	2	66	5	172
Jack	107	3	100	5	264
Julian	75	2	95	4	423
Kashe	127	3	118	5	600
Kamaniske	80	2	82	5	335
Kashagawi	100	2	84	7	249
Kasshabog	76	5	85	6	387
Kimball	170	1	149	7	701
L. Clear	13	3	30	5	289
L. Dore	70	3	70	3	147
Limerick	50	3	53	6	382
Little Ha	70	1	110	6	418
Low Buckh	77	7	78	8	180
Lower Hay	180	1	160	6	536
Matinenda	110	5	141	7	292
Mckenzie	160	1	165	2	465
Methuen	100	1	103	7	321
Mill	170	1	145	4	737
Morrison	130	2	123	6	634
Muskoka	89	9	89	9	917
Oastler	110	1	159	8	399
Oxtongue	50	1	111	7	612
Paudash	160	1	100	5	278
Pike	50	3	84	7	228
Prospect	170	2	125	2	749
Purdy	110	1	116	5	256
Rebecca	130	1	121	7	484
Red Pine	40	1	95	8	308
Robertson	70	1	103	7	350
Robinson	170	1	132	6	375
Round	70	1	100	3	449

TABLE 3 continued.

Round	90	1	129	7	943
Salerno	90	1	85	8	300
Silent	150	1	96	5	408
Six Mile	123	3	114	5	406
St. John	85	2	72	5	377
St. Nora	40	1	107	7	535
Steenburg	107	3	112	5	430
Stony	134	5	117	6	230
Tadenac	40	1	88	3	336
Tasso	120	2	139	8	280
Twelve Mi	80	1	130	6	206
Up Rideau	38	3	38	3	341
Waseosa	160	1	142	5	389
White	80	1	84	7	265
Windermer	30	1	142	9	236
Wollaston	5	1	57	5	665

Avg.	97	2	104	6	403
N	65	65	65	65	65
SD.	43	2	32	2	186
Min.	5	1	30	1	132
Max.	180	9	165	9	943

TABLE 4 Summary of standardized mercury concentration and sediment mercury levels in lake trout lakes.

LAKE TROUT LAKES

Lake Name	Actual Sediment (Hg)(ppb)	Actual N	Avg. 5 Km Sediment (Hg)(ppb)	Average N	Stand. Fish (Hg)(ppb)
Big Porcu	140	1	97	7	289
Bigwind	200	1	133	7	162
Bonnecher	180	1	117	7	348
Burns	68	1	307	8	97
Camp	130	1	121	9	191
Centre	145	1	134	5	260
Clear	70	1	91	7	70
Clearwater	90	1	100	2	162
Clinto	30	1	113	8	75
Cobre	240	1	164	5	114
Cosgrove	40	1	140	5	355
Diamond	150	1	160	4	141
Drag	110	2	131	7	263
Duborne	86	2	115	6	273
Esten	185	1	225	5	194
Flack	64	1	193	6	178
Fletcher	100	1	105	6	200
Grandeur	192	1	128	9	306
Haliburto	105	2	140	6	528
Harp	120	1	110	5	797
Kennisis	105	2	129	8	167
Kimball	170	1	149	7	375
Koshlong	80	1	106	5	735
Lac Aux S	60	1	107	6	263
Limerick	50	3	53	6	258
Little Ha	70	1	110	6	236
Livingsto	230	1	145	8	320
Louisa	180	1	183	7	533
Matinenda	126	4	141	7	224
Mccarroll	166	2	145	6	381
Muskoka	89	9	89	9	1033
Oxtongue	50	1	111	7	514
Papineau	35	2	100	9	293
Percy	150	1	117	6	457
Pine	150	1	152	6	230
Redstone	105	2	137	7	269
Regal	1000	1	304	7	166
Saymo	99	1	150	7	389
Slipper	150	1	102	6	331
Solitaire	70	1	78	5	72
St. Nora	40	1	107	7	639
Tasso	120	2	139	8	123
Twelve Mi	80	1	130	6	328
Avg.	135	1	135	7	310
N	43	43	43	43	43
S.D.	144	1	48	1	200
Min.	30	1	53	2	70
Max.	1000	9	307	9	1033

Table 5 Summary of standardized fish mercury and sediment levels in Walleye lakes.

Lake Name	Actual Sediment Hg (ppb)	Actual N	Avg. 5 Km Sediment Hg (ppb)	Avg. N	Std. Fish Hg (ppb)
Antoine	110	1	80	6	300
Ardoch	40	1	167	6	273
Balsam	80	5	80	5	289
Bay	100	1	138	4	520
Beaver	100	1	125	2	499
Beavertra	120	1	128	9	764
Big Gull	65	2	124	5	573
Biscotasi	188	5		9	570
Bright	83	2	86	5	322
Buckhorn	73	3	73	3	273
Buckshot	95	2	110	6	387
Calabogie	127	3	90	6	568
Cameron	75	4	70	5	510
Canal	95	4	84	5	264
Crosby	70	1	87	3	502
Crotch	70	3	73	4	419
Denyes	40	1	75	11	348
Endikaki	59	1	149	5	649
Eskwannah	70	1	94	8	391
Four Mile	93	3	83	4	242
Fraser	10	2	48	5	490
Golden	60	3	60	3	516
Gordon	59	1	63	2	750
Islington	175	2	150	6	2216
Jack	107	3	100	5	363
Kashe	127	3	118	5	1480
Kashwakam	90	4		9	232
Kashagaw.	100	2	84	7	200
Kasshabog	76	5	85	6	734
L Buckhor	77	7	78	8	266
Nemegosen	42	1	42	1	784
Pike	50	3	84	7	231
Rock	71	1	126	3	1046
Round	70	1	100	3	512
Round	62	5	64	7	614
Skootamat	162	4	130	7	605
St. John	85	2	72	5	432
Stony	134	5	117	6	300
Trappnarr	120	4		6	434
Wakami	21	3		6	128
Widow/Joe	150	1	76	7	291
Windemere	67	6		12	480
Wintering	115	2	91	7	650
Wood	90	2	93	4	335

N	44	44	39	44	44
Avg.	88	3	95	6	517
SD	37	2	29	2	354
Min	10	1	42	1	128
Max	188	7	167	12	2216

Table 6. Summary statistics for variables in smallmouth bass lakes data.

Variable	N	Mean	Range
Std. Fish Hg (ng/g)	66	402	132 - 943
Sed-Hg (ng/g)	66	99	5 - 180
Sed-LOI (%)	66	31.6	0.5 - 67.4
Sed-Zn	66	123	30 - 265
Sed-Cu	66	25.7	8 - 60
Sed-Pb	66	7.7	0.7 - 30.2
Sed-Ni	66	16	4 - 93
Sed-Co	66	11	1 - 76
Sed-Ag	66	0.1	0.1 - 0.2
Sed-Mn	66	815	120 - 3350
Sed-As	66	1.6	0.5 - 5.7
Sed-Mo	66	2.3	1 - 21
Sed-Fe (%)	66	2.7	0.5 - 12.8
Sed-U	66	3.9	0.9 - 29.9
Sed-F	66	151.5	95 - 208
Sed-Cd	47	0.65	0.1 - 1.7
Sed Corg (%)	64	31	1 - 62
Sed-S (%)	64	0.66	0.05 - 2.6
Aq-F (ug/L)	65	61	20 - 251
Aq-pH	66	6.96	5.6 - 8.2
Aq-Alk	66	33.9	1 - 130
Aq-Ca	66	14.1	2.3 - 39.9
Aq-Mg	66	4.4	1.0 - 10.9
Aq-Zn	64	3.6	3.0 - 8.0
Aq-Fe	64	13	10 - 84
Aq-Na	64	2.0	0.6 - 8.6
Aq-K	64	0.73	0.3 - 1.5
Aq-Corg	63	4.3	1.4 - 8.3
Aq-Cl	64	4.5	1.0 - 16.9
Aq-NO ₃	64	0.4	0.2 - 4.1
Aq-SO ₄	64	7.9	4.9 - 13.6
Aq-cond (umhos/cm)	64	86	18 - 246
Lake area (ha)	65	949	35 - 12220
W area (ha)	42	9952	161 - 122500
MNR-pH	55	7.2	6.0 - 8.6
MNR-Alk	54	29.4	0.4 - 98.3
MNR-Cond (umhos/cm)	51	83	26 - 256
MNR-Colour	7	22.6	7 - 41
MNR-Corg	43	4.3	2.2 - 7.4
MNR-Ca	45	10.9	2.1 - 36.3
MNR-Mg	44	1.9	0.5 - 6.8
MNR-Na	43	1.6	0.5 - 3.9
MNR-K	43	0.7	0.3 - 1.4
MNR-SO ₄	45	7.6	4.1 - 11.5

Table 6 Continued.

Variable	N	Mean	Range
MNR-Al	40	0.09	0.0 - 1.5
MNR-Mn	40	0.02	0.0 - 0.07
MNR-Fe	9	0.1	0.0 - 0.3
Max-dep (m)	65	28.3	2.1 - 86.9

Table 7. Significant ($p \leq 0.05$) correlations of LIO-FISH in smallmouth bass with lake variables.

Lake Variable	Pearson Coefficient	N	P
Sediment-Hg	0.31	66	0.006
Sediment-S	-0.38	64	0.001
Sediment-P205	0.37	64	0.001
Sediment-LOI	-0.26	64	0.019
Aq-pH	-0.52	66	0.000
Aq-Alk	-0.50	66	0.000
Aq-Ca	-0.48	66	0.000
Aq-Zn	0.45	64	0.000
Aq-K	-0.32	64	0.005
Aq-SO ₄	-0.43	64	0.000
Aq-Cond	-0.52	64	0.000
MNR-pH	-0.52	55	0.000
MNR-Alk	-0.47	54	0.000
MNR-Cond	-0.43	51	0.001
MNR-Ca	-0.46	45	0.001
MNR-Mg	-0.55	44	0.000
MNR-SO ₄	-0.47	45	0.001
MNR-Fe	0.72	9	0.013
Mean-dep	0.21	64	0.05

Aq = Values from GSC database

MNR = Values from MNR/OME database

Table 8. Summary statistics for variables in Lake Trout lakes data.

Variable	N	Mean	Range
Std. Fish Hg (ng/g)	42	302	70 - 1033
Sed-Hg (ng/g)	42	138	30 - 1000
Sed-LOI (%)	42	28.2	3.0 - 54.4
Sed-Zn	42	127	54 - 230
Sed-Cu	42	35.1	8 - 270
Sed-Pb	42	7.3	1.0 - 78.0
Sed-Ni	42	16.7	8 - 38
Sed-Co	42	11	3 - 29
Sed-Ag	42	0.1	0.1 - 0.4
Sed-Mn	42	890	37 - 3230
Sed-As	42	1.6	0.5 - 6.0
Sed-Mo	42	1.9	1 - 10
Sed-Fe (%)	42	2.7	0.4 - 10.0
Sed-U	42	7.8	0.7 - 85.6
Sed-F	11	136.4	60 - 260
Sed-Cd	39	0.71	0.1 - 1.7
Sed Corg (%)	30	30.6	7.5 - 54.3
Sed-S (%)	30	0.28	0.07 - 0.59
Aq-F (ug/L)	42	43	20 - 74
Aq-pH	42	6.38	5.4 - 7.8
Aq-Alk	41	7.3	1 - 92.9
Aq-Ca	41	4.5	2.0 - 36.9
Aq-Mg	41	5.2	1.0 - 9.6
Aq-Zn	30	4.3	3.0 - 11.0
Aq-Fe	30	12	10 - 50
Aq-Na	30	1.0	0.4 - 3.1
Aq-K	30	0.49	0.2 - 1.3
Aq-Corg	30	2.9	1.3 - 6.6
Aq-Cl	30	3.5	1.0 - 9.8
Aq-NO ₃	30	0.4	0.2 - 1.0
Aq-SO ₄	30	7.4	5.4 - 10.1
Aq-cond (umhos/cm)	30	33	18 - 179
Lake area (ha)	39	748	13 - 12210
W area (ha)	18	5566	239 - 44780
MNR-pH	42	6.6	5.6 - 8.0
MNR-Alk	40	7.6	0.4 - 94.8
MNR-Cond (umhos/cm)	42	46	24 - 213
MNR-Colour	20	15.3	0 - 47
MNR-Corg	32	3.2	0.3 - 6.1
MNR-Ca	39	4.8	2.0 - 35.8
MNR-Mg	32	1.0	0.5 - 3.4

Table 8 Continued.

Variable	N	Mean	Range
MNR-Na	32	1.5	0.4 - 8.7
MNR-K	32	0.5	0.3 - 1.3
MNR-SO ₄	34	8.9	6.0 - 19.2
MNR-Al	29	0.02	0.0 - 0.05
MNR-Mn	31	0.02	0.0 - 0.02
MNR-Fe	6	0.05	0.0 - 0.13
Max-dep (m)	39	41.3	14.5 - 86.9

Table 9. Significant correlations ($p < 0.05$) of log standardized mercury with lake variables in lake trout lakes.

fish

Lake variable	Pearson Coefficient	N	P
Lake area	0.57	38	0.000
MNR-Corg	0.43	31	0.008

Table 10. Summary statistics for variables in walleye lakes data.

Variable	N	Mean	Range
Std. Fish Hg (ng/g)	44	517	128 - 2216
Sed-Hg (ng/g)	44	88	10 - 188
Sed-LOI (%)	44	28.0	5 - 73.4
Sed-Zn	44	104	19 - 214
Sed-Cu	44	25.6	9 - 50
Sed-Pb	44	7.3	0.5 - 30.2
Sed-Ni	44	16	2 - 39
Sed-Co	44	9	1 - 19
Sed-Ag	44	0.1	0.1 - 0.15
Sed-Mn	44	652	80 - 2500
Sed-As	44	1.5	0.5 - 3.6
Sed-Mo	44	1.7	1 - 5.3
Sed-Fe (%)	44	2.3	0.2 - 7.1
Sed-U	44	4.6	0.7 - 15.5
Sed-F	9	226.9	60 - 350
Sed-Cd	22	0.43	0.1 - 1.0
Sed Corg (%)	30	31	8 - 69
Sed-S (%)	30	0.78	0.14 - 2.6
Aq-F (ug/L)	44	61	24 - 251
Aq-pH	44	7.3	5.9 - 8.2
Aq-Alk	39	41.4	3 - 108
Aq-Ca	39	16.1	0.1 - 46.5
Aq-Mg	39	2.4	0.1 - 6.2
Aq-Zn	30	3.2	3.0 - 5.0
Aq-Fe	30	10.0	10 - 10
Aq-Na	30	1.8	0.5 - 5.0
Aq-K	30	0.86	0.4 - 1.4
Aq-Corg	30	4.8	2.0 - 7.7
Aq-Cl	30	2.1	0.3 - 9.0
Aq-NO ₃	30	0.7	0.2 - 4.1
Aq-SO ₄	30	7.9	3.2 - 11.1
Aq-cond (umhos/cm)	30	110	23 - 256
Lake area (ha)	16	1164	121 - 3552
W area (ha)	1	14820	
MNR-pH	19	7.3	6.2 - 8.4
MNR-Alk	16	28.6	2.6 - 89.4
MNR-Cond (umhos/cm)	12	88	34 - 200
MNR-Colour	0		
MNR-Corg	0		
MNR-Ca	0		
MNR-Mg	0		
MNR-Na	0		
MNR-K	0		
MNR-SO ₄	0		
MNR-Al	0		
MNR-Mn	0		
MNR-Fe	0		
Max-dep (m)	41	24.8	2.1 - 93.0

Table 11. Significant correlations ($p < 0.05$) of log standardized fish mercury with lake variables in walleye lakes.

Lake variable	Pearson Coefficient	N	P
Sed-Hg	0.39	44	0.004
Aq-pH	-0.28	44	0.003
Aq-Alk	-0.51	39	0.000
Aq-Ca	-0.48	39	0.001
Aq-Mg	-0.45	39	0.002
Aq-SO ₄	-0.44	30	0.007
Aq-Cond	-0.52	30	0.002



FIGURE 1. Areas sampled for lake sediment Hg levels by GSC.

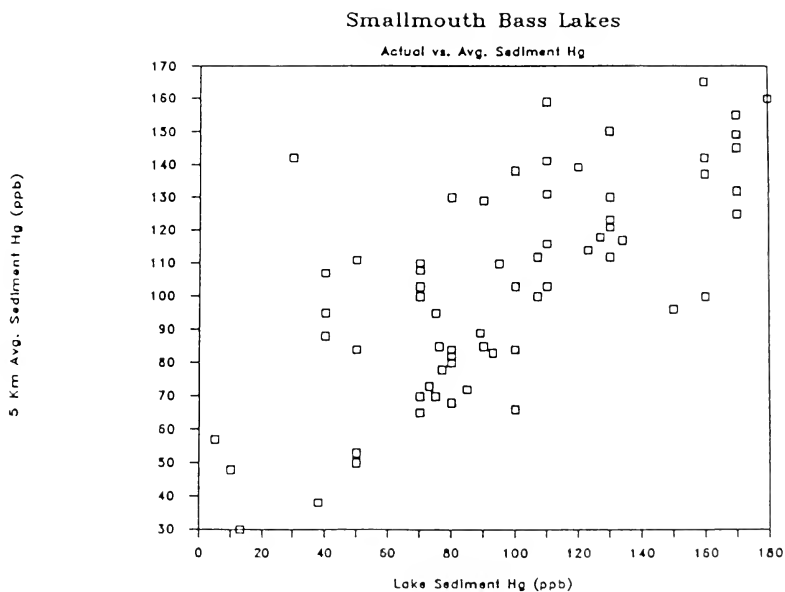
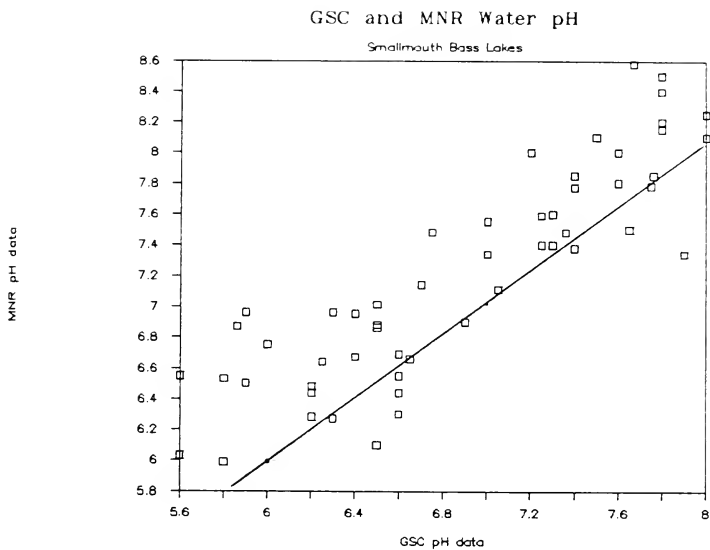


FIGURE 2. Relationship between actual lake sediment mercury concentration and 5 km average mercury concentration.



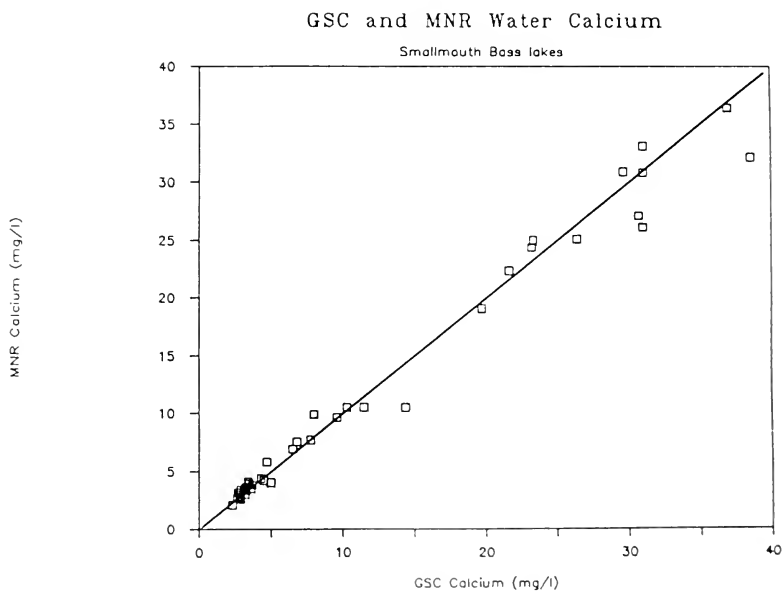


FIGURE 3b. Comparison of GSC and MNR/OME
Lake calcium concentration water quality data

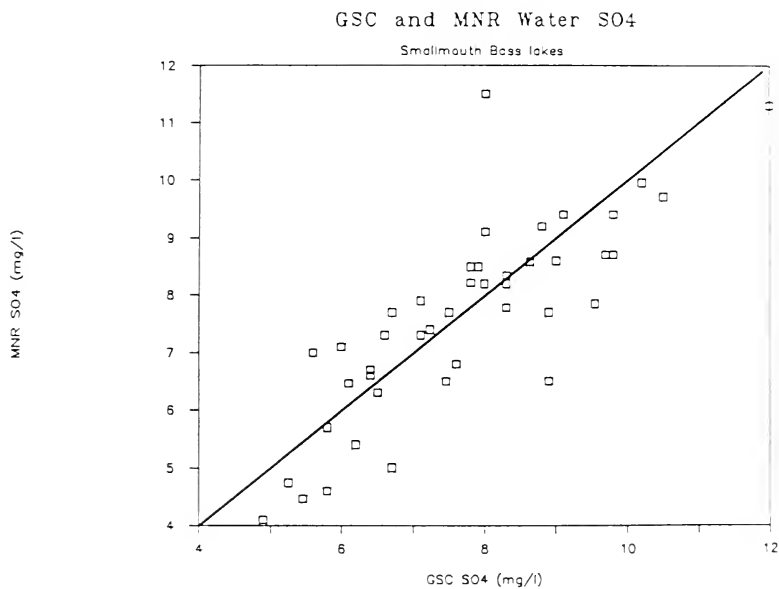


FIGURE 3c. Comparison of GSC and MNR/OME
Lake SO₄ concentration water quality data.

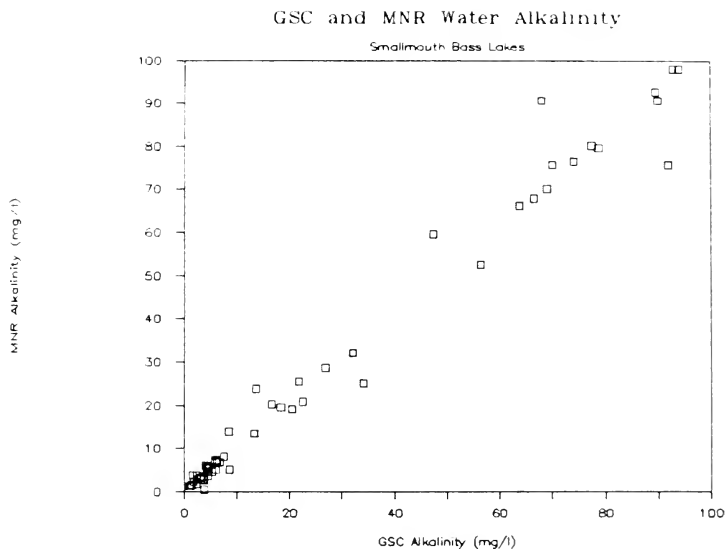


FIGURE 3d. Comparison of GSC and MNR/ONE Lake alkalinity over full range of lake conditions water quality data.

GSC and MNR Water Alkalinity

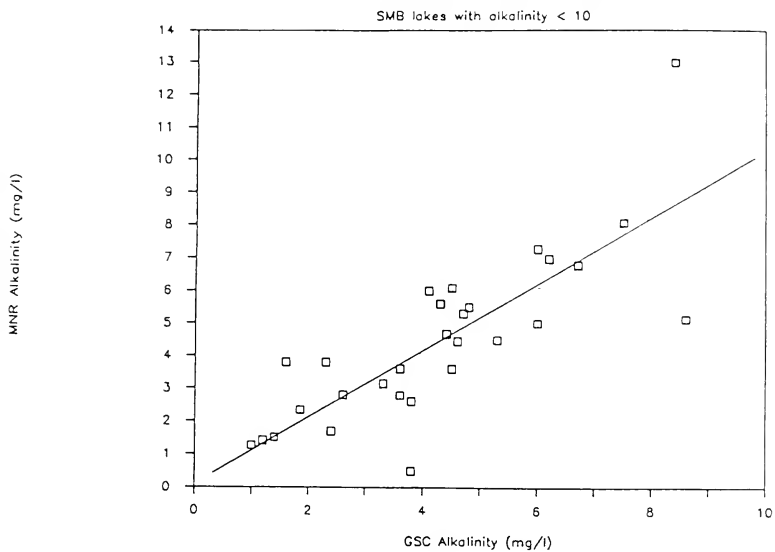


FIGURE 3e. Comparison of GSC and MNR/MOE Lake alkalinity for lakes with alkalinity < 10mg/l water quality lakes.

Comparison of GSC and MNR/OME Water Conductivity Data Values

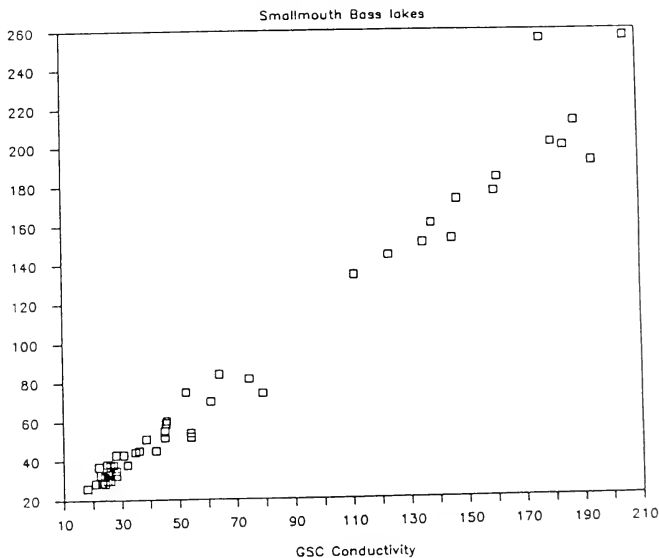


FIGURE 3f. Comparison of GSC and MNR/OME Lake conductivity water quality data.

Smallmouth Bass Lakes

Actual Sediment Hg vs. Fish Hg

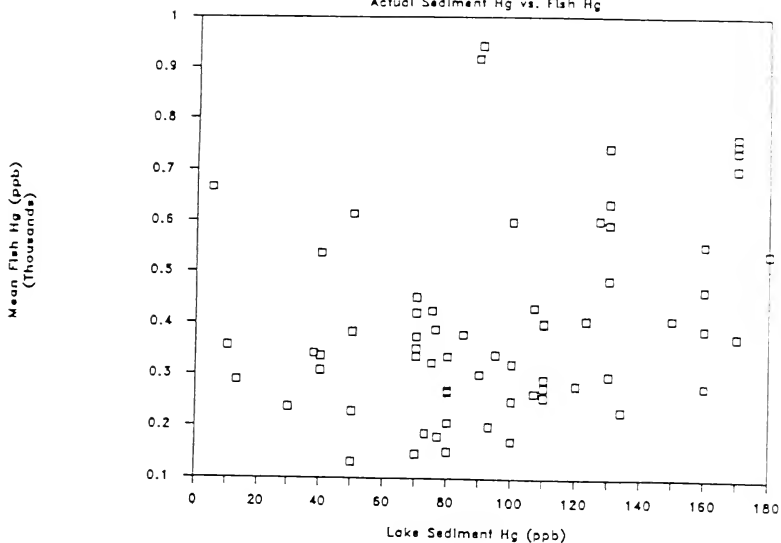


FIGURE 4. Relationship between standardized mercury concentration in smallmouth bass and sediment mercury concentration.

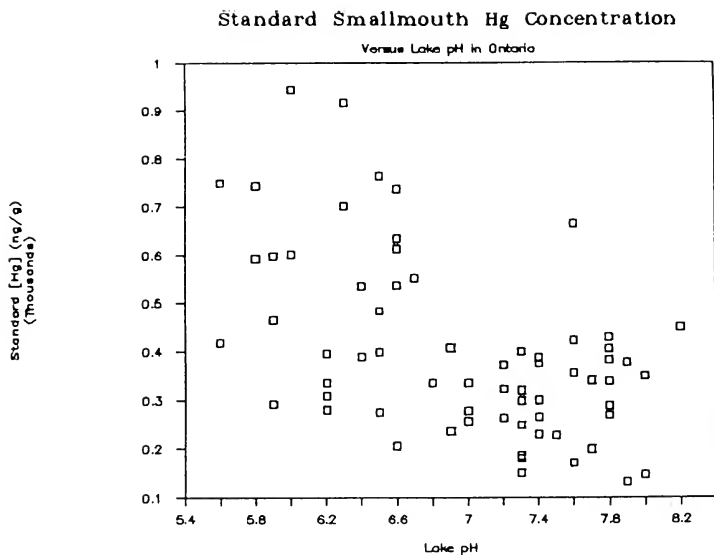


FIGURE 5. Relationship between standardized mercury concentration in smallmouth bass and lake pH.

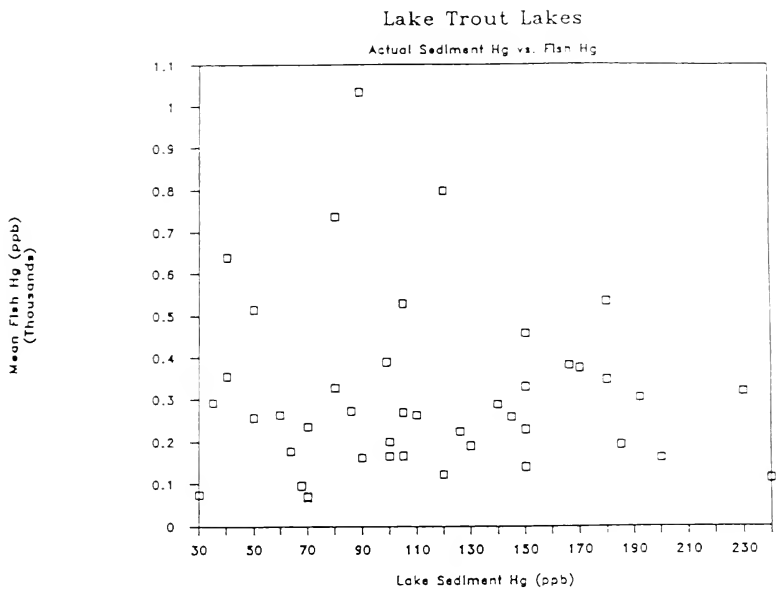


FIGURE 6. Relationship between standardized mercury concentration in lake trout and sediment mercury concentration.

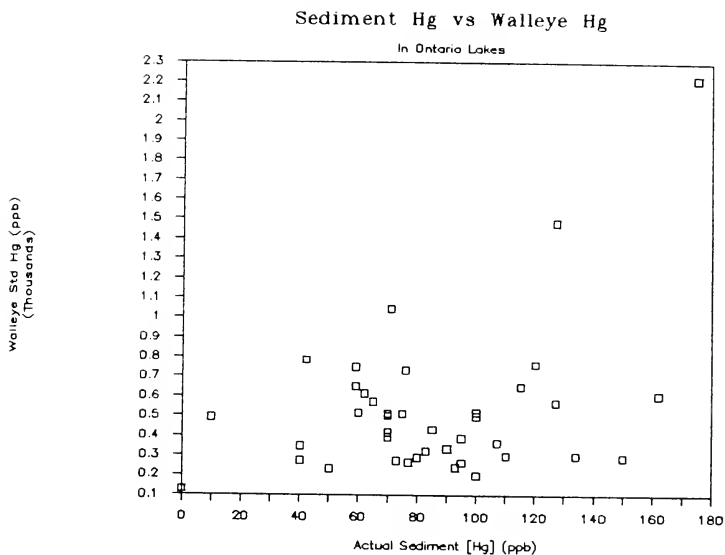


FIGURE 7. Relationship between standardized mercury concentration in walleye and sediment mercury concentration.

Smallmouth Bass Hg vs Walleye Hg

In Ontario Lakes

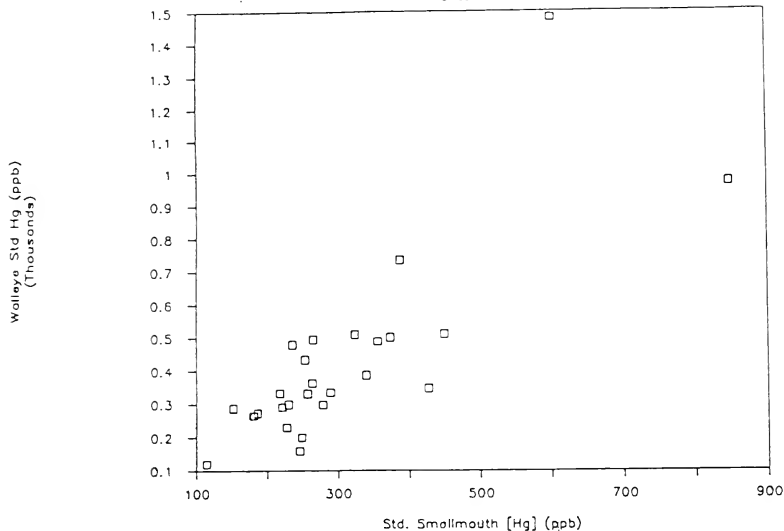


FIGURE 8. Relationship of standardized mercury concentration in smallmouth bass with walleye standardized mercury concentration.

SMB Std. Hg vs. L. Trout Std. Hg

In Overlapping Lakes

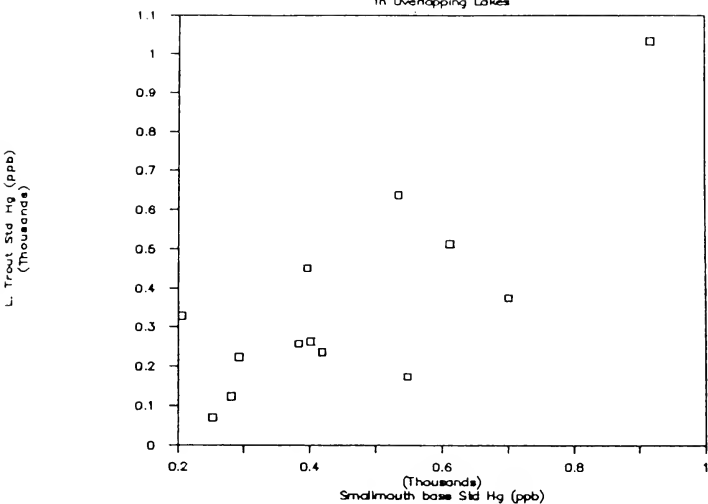


FIGURE 9. Relationship of standardized mercury concentration in smallmouth bass with lake trout standardized mercury concentration.

